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Auditory Weighting Functions and Frequency-Dependent Effects of Sound in Bottlenose Dolphins (*Tursiops truncatus*)

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LONG-TERM GOALS

The long term goal of this effort is to develop meaningful auditory weighting functions for marine mammals. These weighting functions would improve assessments of the effects of anthropogenic sound by emphasizing frequencies to which animals are most sensitive and de-emphasizing those to which they are not.

OBJECTIVES

The objective of this effort is to develop auditory weighting functions for bottlenose dolphins with normal hearing and high-frequency hearing loss. The weighting functions would be defined by measuring subjective loudness and temporary threshold shift (TTS) as functions of the sound frequency.

The specific objectives for FY09 were to (1) determine TTS onset/growth as a function of frequency for 16-s tones using single and multiple auditory evoked potential (AEP) and behavioral measurements in a bottlenose dolphin with high-frequency hearing loss, (2) determine equal loudness contours using behavioral methods in a second bottlenose dolphin with good high-frequency hearing.

APPROACH

TTS is defined as the difference between hearing thresholds measured before and after an intense (fatiguing) sound exposure. Hearing thresholds are estimated using either a behavioral response paradigm, where the subject is trained to perform a specific action when it hears a test tone, or an electrophysiological method, where AEPs are measured in response to test tones. Hearing tests are typically conducted ~1/2-octave above the exposure frequency, where the largest TTS is expected.

Behavioral methods developed at the Navy Marine Mammal Program (MMP) allow thresholds to be obtained within four minutes of intense sound exposures. This is accomplished using computer-controlled stimulus presentations, recording acoustic responses emitted by the subject in response to those stimuli, and presenting multiple trials before subject reinforcement. Dolphins typically produce an acoustic response (a whistle or burst pulse) within a few hundred milliseconds of tone onset, allowing a rapid pace of stimulus presentation and fast threshold estimates. A modified up/down

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long term goal of this effort is to develop meaningful auditory weighting functions for marine mammals. These weighting functions would improve assessments of the effects of anthropogenic sound by emphasizing frequencies to which animals are most sensitive and de-emphasizing those to which they are not.

15. SUBJECT TERMS

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descending staircase technique is used to adjust the stimulus level in an adaptive fashion from one trial to the next and bracket the threshold.

Electrophysiological thresholds are estimated by measuring a type of AEP called an auditory steady state response (ASSR). Hearing tests are conducted underwater using a stimulus projected in the direct field stimulus (not via a "jawphone"). A statistical test (magnitude-squared coherence) is used to objectively determine the presence or absence of AEPs in response to stimuli at different levels. Thresholds are based on the lowest detectable response with a 1% probability of false detection.

Subjects are trained to wear suction cup-mounted hydrophones during the fatiguing sound exposures to allow estimates of the received sound levels regardless of subject location. Pure-tone exposures are characterized by the average sound pressure level (SPL), sound exposure level (SEL), and exposure duration. Tests are conducted in a quiet, above ground test pool.

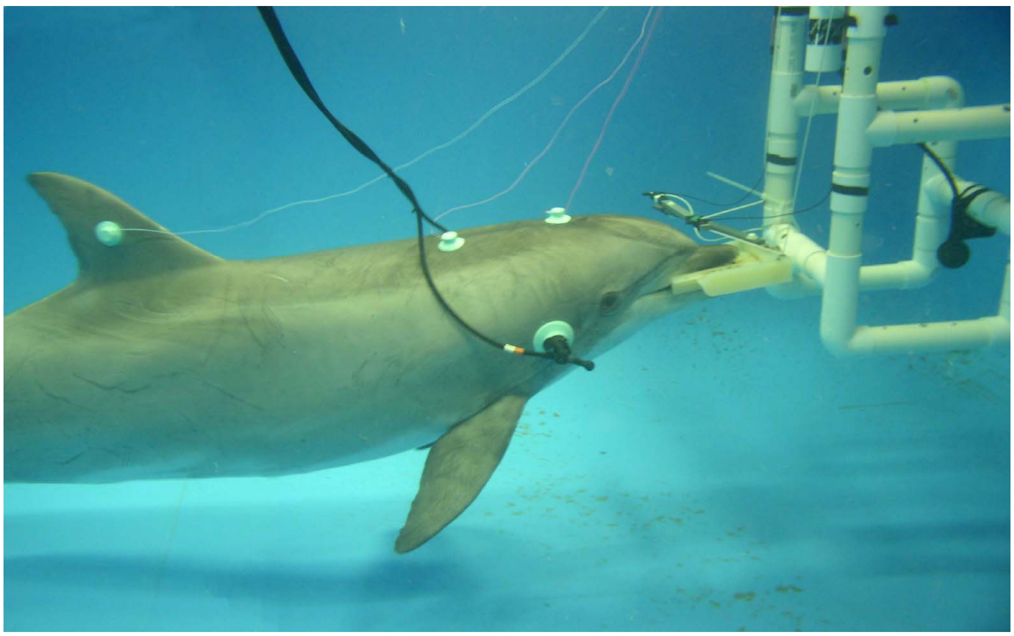

Figure 1. A dolphin subject in the pool during a TTS experiment. Suction cup-mounted hydrophones placed near the ears are used to record the sound levels during the fatiguing sound exposure. Surface electrodes embedded in small suction cups placed on the head and back are used to measure AEPs.

Equal loudness tests use a loudness comparison method where the subject is presented two sequential tones. The subject is trained to whistle if the first tone is louder than the second and to produce a burst pulse or "buzz" response if the second tone is louder than the first. The majority of trials feature stimulus pairs for which the loudness relationship between the two tone pairs is known, for example two tones at the same frequency but with different SPLs. The subject's performance on the "known" trials allows its performance to be tracked within each session. Approximately 29% of the trials are probe trials, consisting of a standard tone, whose frequency and SPL are fixed, and comparison tone, whose frequency is fixed within a session but whose SPL varies. The order in which the standard and comparison tones are presented is balanced within each session. The subject's responses to the probe

trials are analyzed using logistic regression to derive curves relating the probability of the comparison tone being perceived louder for each comparison tone frequency. The 50% point then represents the SPL at which the comparison tone was equally loud as the standard. This method is similar to methods used to derive equal loudness curves in humans.

James Finneran served as the PI and project manager, developed the hardware and software for AEP and behavioral hearing tests and the loudness comparison tests, analyzed the acoustic and threshold data, and performed the TTS mathematical modeling. Carolyn Melka served as the technical coordinator for the threshold, TTS, and equal loudness tests conducted in the pool, conducted the daily experiments, calibrated the sound system, and analyzed/archived the resulting data. Brian Branstetter and Laura Yeates assisted with data collection and analysis.

WORK COMPLETED

We completed a total of 101 control sessions and 54 fatiguing exposure sessions with the dolphin BLU (age 43 y). Fatiguing exposure durations were 16 s; frequencies ranged from 3 kHz to 40 kHz. Frequencies above 40 kHz were not tested because the affected frequency range would have been beyond the upper limit of BLU’s hearing.

We completed a total of 157 equal loudness sessions (16 678 trials) in the dolphin TYH (age 27 y). The standard tone frequency was 10 kHz, with SPLs of 90, 105, and 115 dB re 1 µPa. Comparison frequencies ranged from 3.5 to 113.1 kHz. At each frequency, we obtained between 200 and 1100 individual data points.

RESULTS

TTS growth in BLU at 3 kHz (Fig. 2) was significantly different than TTS growth measured in her previously (c. 2004–2007), despite no change in pre-exposure thresholds over this same time period. The reason for the increased susceptibility to noise exposure is unknown. From 2007–2008, BLU had a calf and was nursing; she continued to nurse the calf during the early part of 2009 and the calf was weaned during the summer of 2009; however, there is no reason to believe this was the underlying cause of the change in TTS results. There may be some underlying cochlear or nervous system pathology that acts synergistically with noise exposure to result in elevated TTS, even though the pathology is not significant enough by itself to produce a measurable change in baseline hearing thresholds. The change may be simply the result of aging: changes in hair cell and cochlear physiology that occur with aging may result in the hair cells being unable to recover from fatigue (e.g., metabolic exhaustion) as quickly as in the past. This result is significant because it goes against the common assumption that the youngest animals would be the most susceptible to noise exposure; although older animals may lose sensitivity, they may also lose the ability to recover from fatigue and may thus remain at risk to overexposure to noise.

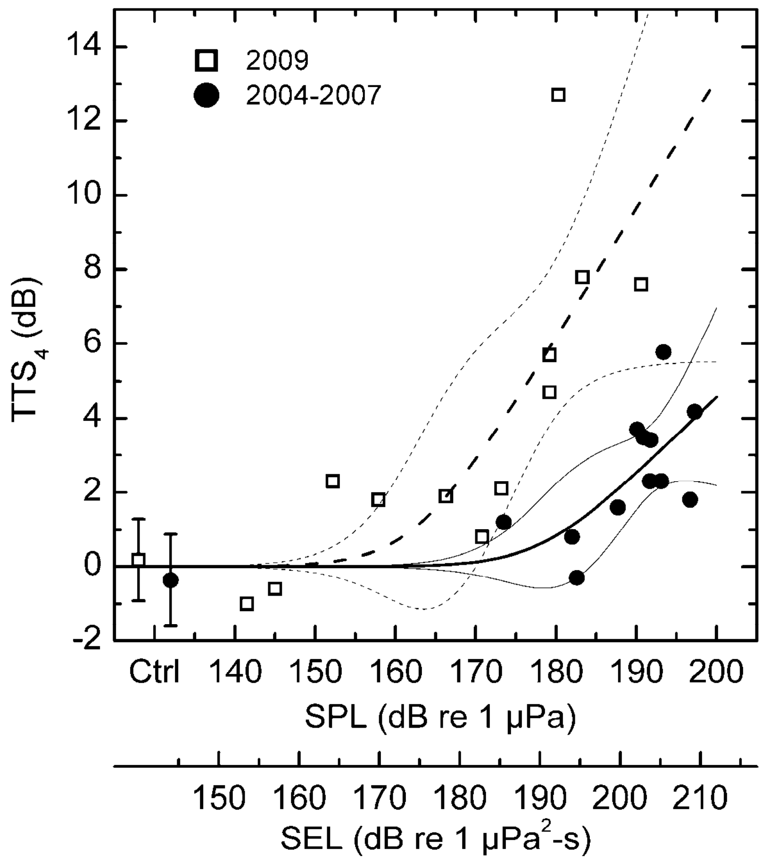

Figure 2. TTS growth in a bottlenose dolphin after 3-kHz exposures. Hearing was tested at 4.5 kHz, about 1/2-octave above the exposure frequency. The amount of TTS grows exponentially with the exposure SEL at low levels; at higher levels the growth is approximately linear. Significant differences were observed between data collected in 2004-2007 and those collected in 2009, with the more recent data showing a higher growth rate, indicating that the subject is more susceptible to TTS now compared to two years ago.

TTS measurements in BLU at various frequencies across her range of hearing allowed us to define the growth and onset of TTS for exposures from 3 to 40 kHz. These data (Figs. 3 and 4) reveal substantial differences between onset-TTS levels and TTS growth rates. This means TTS will occur at lower exposure levels, and increase more rapidly with increasing exposure level, as frequencies increase beyond 3 kHz. Consequently, acoustic impact thresholds based on 3-kHz data are not appropriate for 10, 20, or 28-kHz exposures – they will underestimate the effects. It is also important to note that the difference between the onset of TTS at various frequencies is not simply the difference in thresholds – the thresholds at 10, 20, and 28 kHz are almost equivalent and are 10–15 dB lower than those at 3 kHz, not the ~20–30 dB difference observed in the exposures sufficient to cause TTS at increasingly higher frequencies. Exposures at 40 kHz did not produce TTSs at or above the exposure frequency presumably due to the subject’s existing high-frequency hearing loss.

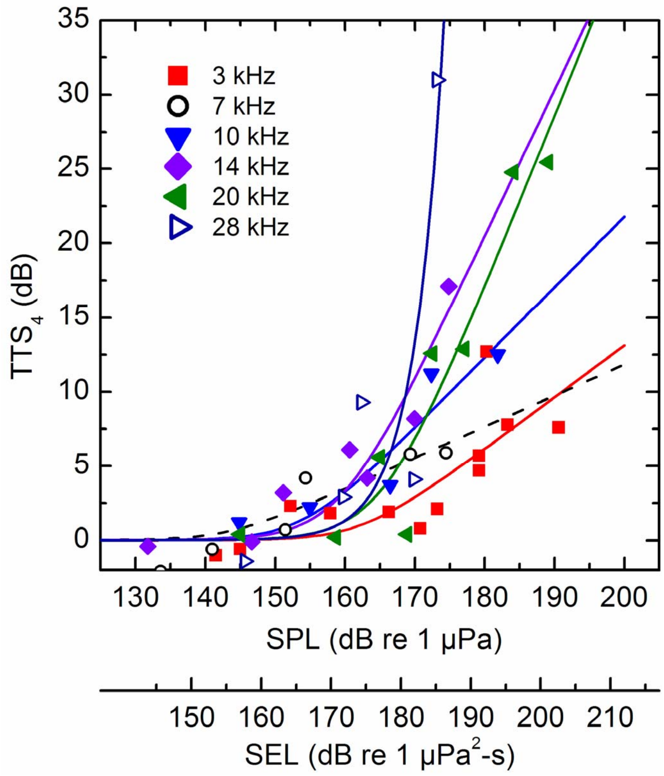

Figure 3. TTS as a function of SEL for 16-s exposures at 3, 7, 10, 14, 20, and 28 kHz. Hearing was tested at 4.5, 10, 14, 20, 30, and 40 kHz, respectively, using behavioral and electrophysiological methods. The onset of TTS exposures at increasingly higher frequencies was significantly lower than the onset of TTS for 3-kHz exposures.

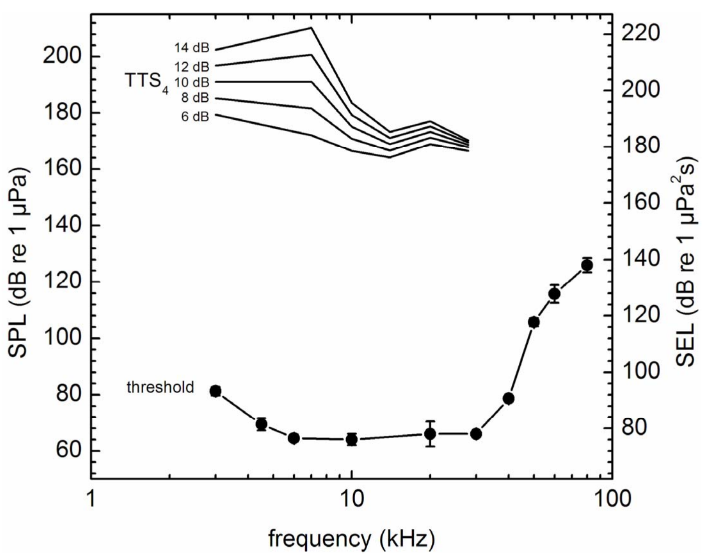

Figure 4. Comparison between iso-TTS contours and behavioral thresholds in BLU. TTS onset levels (i.e., TTS_4 = 6 dB) for 16-s exposures are roughly 100 dB above thresholds, but the difference in growth rates results in increasing differences between exposure levels required for specific values of TTS at different exposure frequencies.

Figure 5 shows preliminary equal-loudness contours measured in the dolphin TYH. Human weighting schemes were derived from equal-loudness curves such as those in Fig. 5. The data obtained from this study represent the first direct measurement of equal-loudness curves in any animal. The shape of the equal-loudness contours can be used to create weighting functions to properly emphasize frequencies at which auditory sensitivity is highest and lessen the importance of other frequencies, similar to human A- and C-weighting networks.

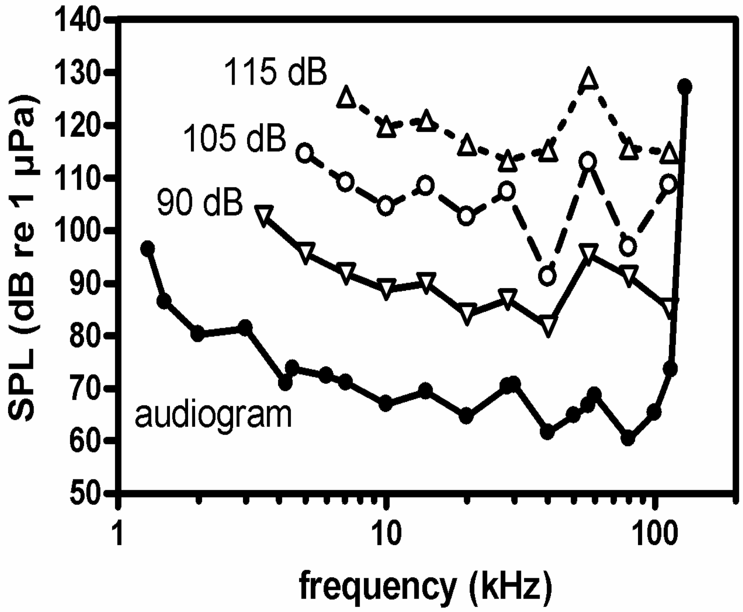

Figure 5. Preliminary equal-loudness contours passing through 10 kHz at 90, 105, and 115 dB SPL. The equal-loudness contours tend to parallel the audiogram (the hearing threshold as a function of frequency), but diverge at the highest frequencies.

IMPACT/APPLICATIONS

The observed differences between TTS onset at 3, 7, 10, 14, 20, and 28 kHz will affect the manner in which Navy predicts auditory effects of high-frequency sonars on wild marine mammals. At present, onset-TTS data from dolphins tested at mid-frequencies (primarily 3 kHz) are used to make predictions at all other frequencies. Data at higher frequencies will be used to create frequency-dependent estimates for onset-TTS (i.e., TTS weighting functions) that are more accurate than current estimates.

Similarly, the equal loudness data show the relationship between the frequency of sound and the subjective loudness of the sound. Weighting functions created from these data may be more appropriate to assessing behavioral effects of sound, under the assumption that the behavioral reactions of animals are more strongly related to the *loudness* of a sound compared to the *SPL* of the sound.

TRANSITIONS

Data resulting from this project have been presented at scientific conferences, briefed to ONR, NMFS, and CNO N45, and published in peer-reviewed scientific journals. The TTS data are often used in

environmental assessments and impact statements that must be prepared for weapons systems development, surveillance systems development, quality assurance tests, oceanographic research, and training exercises. The TTS data that have been collected to date have been used extensively by Navy environmental analysts and have been used to derive acoustic impact criteria for various EAs and EISs, including the SEAWOLF Shock Trial, the WINSTON CHURCHILL Shock Trial, MESA VERDE (LPD 19) Shock Trial, USWTR, HRC, SOCAL, and AFAST EISs. These data have also affected decision making on naval exercises such as RIMPAC and provided the basis for deconfliction guidelines for US Navy Marine Mammal Systems operating near active acoustic sources. The TTS data are used by not only the US Navy, but also by various NATO allies and the seismic industry for predicting and mitigating effects of sonars and explosives on marine mammals.

The AEP system software developed at the Navy MMP (called EVREST — the Evoked Response Study Tool) has been shared with other researchers conducting AEP measurements, including those at UC Santa Cruz (Colleen Reichmuth and Marissa Ramsier), University of South Florida (David Mann), and the Pennsylvania State University Applied Research Lab (Mardi Hastings).

RELATED PROJECTS

"Temporary threshold shift (TTS) in odontocetes in response to multiple airgun impulses," is a related project funded by the International Association of Oil and Gas Producers, Joint Industry Project (JIP). This effort employs techniques and equipment for behavioral and AEP hearing tests developed under previous ONR efforts.

"Electrophysiological techniques for sea lion population-level audiometry," is a related project funded by ONR (N0001409WR20202). This effort employs techniques and equipment for behavioral and AEP hearing tests developed under previous ONR efforts.

PUBLICATIONS

Finneran, J. J., Carder, D. A., Schlundt, C. E., and Dear, R. L. (2009). "Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones," J. Acoust. Soc. Am. [submitted, refereed]

Finneran, J. J., Carder, D. A., Schlundt, C. E., and Dear, R. L. (2009). "Growth and recovery of temporary threshold shift (TTS) at 3 kHz in bottlenose dolphins (*Tursiops truncatus*)," J. Acoust. Soc. Am. [in press, refereed]

Finneran, J. J., Houser, D. S., Mase-Guthrie, B., Ewing, R. Y., and Lingenfelser, R. G. (2009). "Auditory evoked potentials in a stranded Gervais' beaked whale (*Mesoplodon europaeus*)," J. Acoust. Soc. Am. 126, 484-490. [published, refereed]

Finneran, J. J. (2009). "Evoked Response Study Tool (EVREST): a portable, rugged system for single and multiple auditory evoked potential measurements," J. Acoust. Soc. Am. 126, 491-500. [published, refereed]

Finneran, J. J. (2008). "Modified variance ratio for objective detection of transient evoked potentials in bottlenose dolphins (*Tursiops truncatus*)," J. Acoust. Soc. Am. 124, 4069-4082. [published, refereed]

HONORS/AWARDS/PRIZES

James Finneran, SSC San Diego Publication Award, Distinguished, Open Literature, 2007

James Finneran, SSC San Diego Publication Award, Honorable Mention, Open Literature, 2007

James Finneran, SSC San Diego Publication Award, Honorable Mention, Open Literature, 2007

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